

Lund Observatory: March 2009

The expansion of The Universe and The Cosmic Microwave Background

Michael Way

NASA/GISS & NASA/Ames

<http://astrophysics.arc.nasa.gov/~mway/EXP.pdf>

Planck: “A new scientific truth doesn’t triumph by convincing its opponents of that truth, but because they eventually die & a new generation grows up that is familiar with that truth”

Observational Cosmology Pre-1900

1745 Pierre de Maupertuis: Nebular stars are dense crowds of small stars

1750 Thomas Wright: Milky Way is flattened

1755 Immanuel Kant: speculates that elliptical stars of Maupertuis are galaxies (**island universes**)

1799-1805: LaPlace: 'Mécanique Céleste'

1868 William Huggins: first stellar doppler shift measured

1912: Vesto Melvin Slipher

First to discover a large spectral shift for a spiral nebula (blue shift in fact)

- From Lowell Observatory's 24" telescope
 - 6h50m exposure time (September 17, 1912)
- Was traveling at an incredible -300 km/s

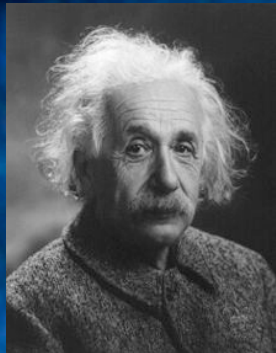


Isaac Roberts (1899) 20" reflector



Pease (1918)

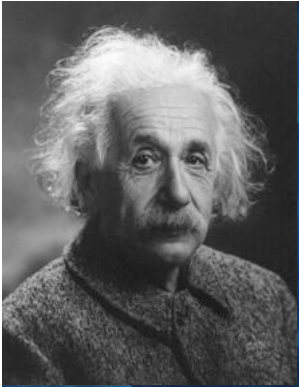




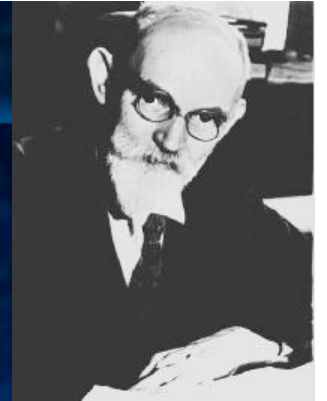
Albert Einstein: 1915 & 1916

Develops the theory of General Relativity

$$G_{ab} + \Lambda g_{ab} = kT_{ab}$$



Einstein & de Sitter: 1917



Two cosmological models quickly arise :

A.) Einstein's static (closed) matter filled world

- Homogeneously filled with dilute matter
- Contained a definite mass
- In equilibrium, no internal pressures or stresses

B.) Willem de Sitter's static (closed) empty Universe

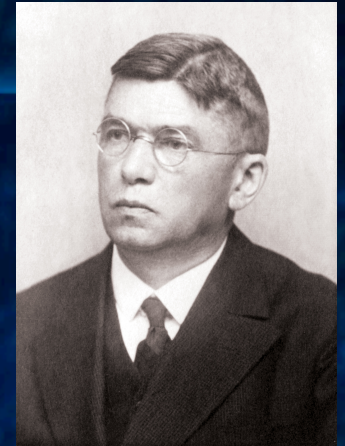
- If more than 1 particle, these cannot be at rest
- He predicted "spurious positive radial velocities" for distant objects
- They were not regarded as coming from the expansion of space (this is **still** a "static" model)

1917: Vesto Melvin Slipher



- 1917: Reported radial velocities of nearly 25 nebulae (21 redshifted)
 - Four had velocities greater than 1000 km/s
- NO conception that these might be interpreted in terms of an expanding universe or even a De Sitter one.
 - Recurring theme: Observers vs Theorists
 - 1925: reported 45 nebulae (41 redshifted)

1918/21: Carl Wilhelm Wirtz

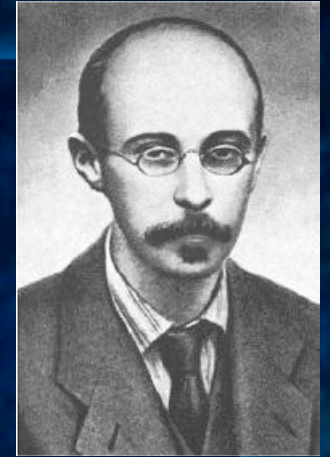


- One of the first to use Airy's equation of solar motion with Cambell's K constant of nebular motion using a "decent" sample & fit
 - 16 nebular radial velocities via Paddoc (1916)
 - $v = X \cos \alpha \cos \delta + Y \sin \alpha \cos \delta + Z \sin \delta + K$
 - $v_{\text{solar}} = -831 \text{ km/s}$, $K_{\text{nebulae}} = +656 \text{ km/s}$
- "*If one gives this value a literal interpretation, the system of spiral nebulae disperses with the velocity 656 km/s relative to the momentary position of the solar system as center.*"
- 1921: Describes a linear relationship between nebular magnitudes and velocities in an unpublished diagram

Radioactive Dating of the Earth

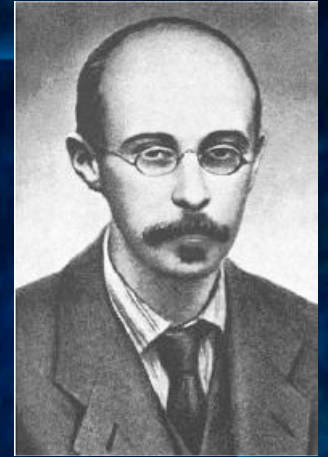
- 1921: H.N. Russell: 4×10^9 yrs is max age of Earth's crust via radioactive dating of Thorium & Uranium
- 1929: Rutherford: 3.4×10^9 yrs via U-235 and U-238
- 1930s: $2-3 \times 10^9$ yrs is accepted age of Earth using radioactive dating techniques

Alexander Friedman (1922)



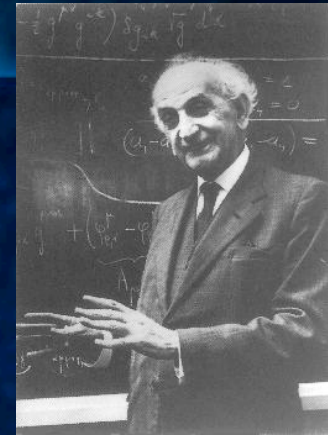
- Additional solutions to Einstein's GR eqns
 - Including a non-static matter-filled **world** model solution
- “The purpose of this note is to show that the cylindrical (Einstein) and spherical (de Sitter) worlds are special cases of more general assumptions, and to demonstrate the possibility of a world in which the curvature of space is independent of the 3 spatial coordinates but does depend on time” $R=R(t)$
- For illustration he used $\Lambda=0$ and $M=5 \times 10^{21} M_{\text{sun}}$ giving a world model age of about 10^{10} yrs

Alexander Friedman (1922)



- BUT...
- “our knowledge is completely insufficient for a numerical comparison to decide which world is ours”
- The papers are of a purely mathematical nature
- There was NO attempt to incorporate physics or astronomy
- Sent a copy to Einstein – a “discussion” ensued and eventually these solutions are forgotten?

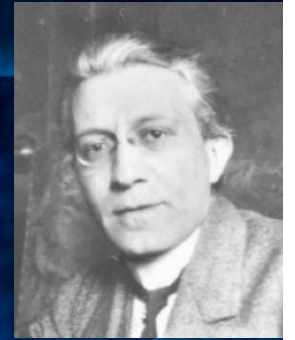
Cornelius Lanczos (1922/3)



- 1922: Realizes it is possible to discard the static nature of the de Sitter model
- 1923: Publishes the model in detail
 - Inspired by a paper by Weyl 1923 Phys. Z. 24, 130
- Replaces the constant radius of curvature R of de Sitter & Einstein with a time variable scale factor $R(t)$



Weyl & Silberstein (1923-4)



- 1923: Hermann Weyl shows (indirectly) a linear relationship between redshift and distance (theoretically) in de Sitter's theory
- 1924: Ludwik Silberstein argues for a relation of the form $\Delta\lambda/\lambda = \pm r/R$ (red & blue shift!)
 - Claims it agrees with observations of globular clusters (only uses 7 of 16 data pts)
 - The “Silberstein Effect” is ridiculed
 - Neither Weyl or Eddington support the red/blue shift effect



Edwin Hubble (1923/25)

- 1923/10 Found Cepheids in Andromeda (M31)
 - First found in a spiral nebula
 - Has access to 100" Hooker
- 1925/01 Publishes distance of 300 kpc
- 1925: Establishes that spiral nebulae **are external galaxies**
 - Supports island universe idea (Kant 1755)
 - Partial resolution of Shapley-Curtis debate



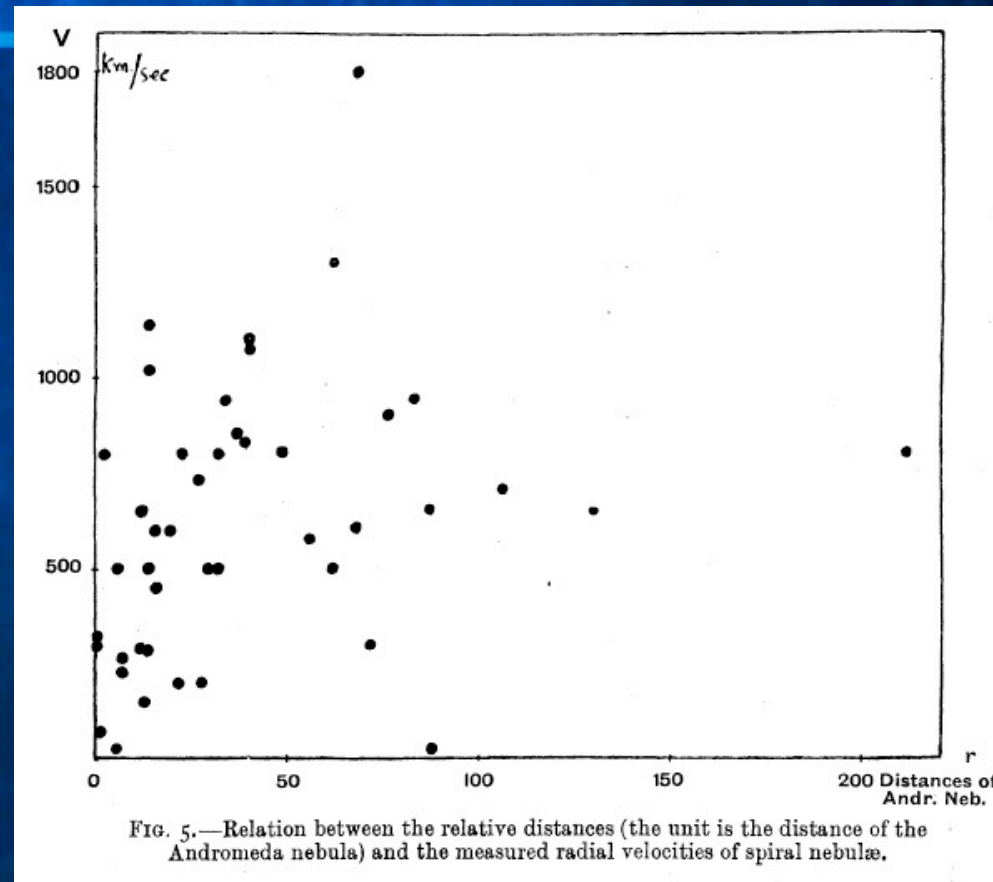


Knud Lundmark (1924-25)

- Is puzzled by Silberstein's derivations
- Says G.C.s are too close to measure R & sees no correlation between v & r for them
- Also tests Cepheids, Novae, O Stars, Eclipsing Variables, R Stars, N Stars
 - 1924 MNRAS 84, 747
- Plots 38 nebular distances vs radial velocity
 - Distance via nebular diameters and magnitudes
 - "There may be a relation between the two quantities, although not a very definite one"



Knut Lundmark (1924)

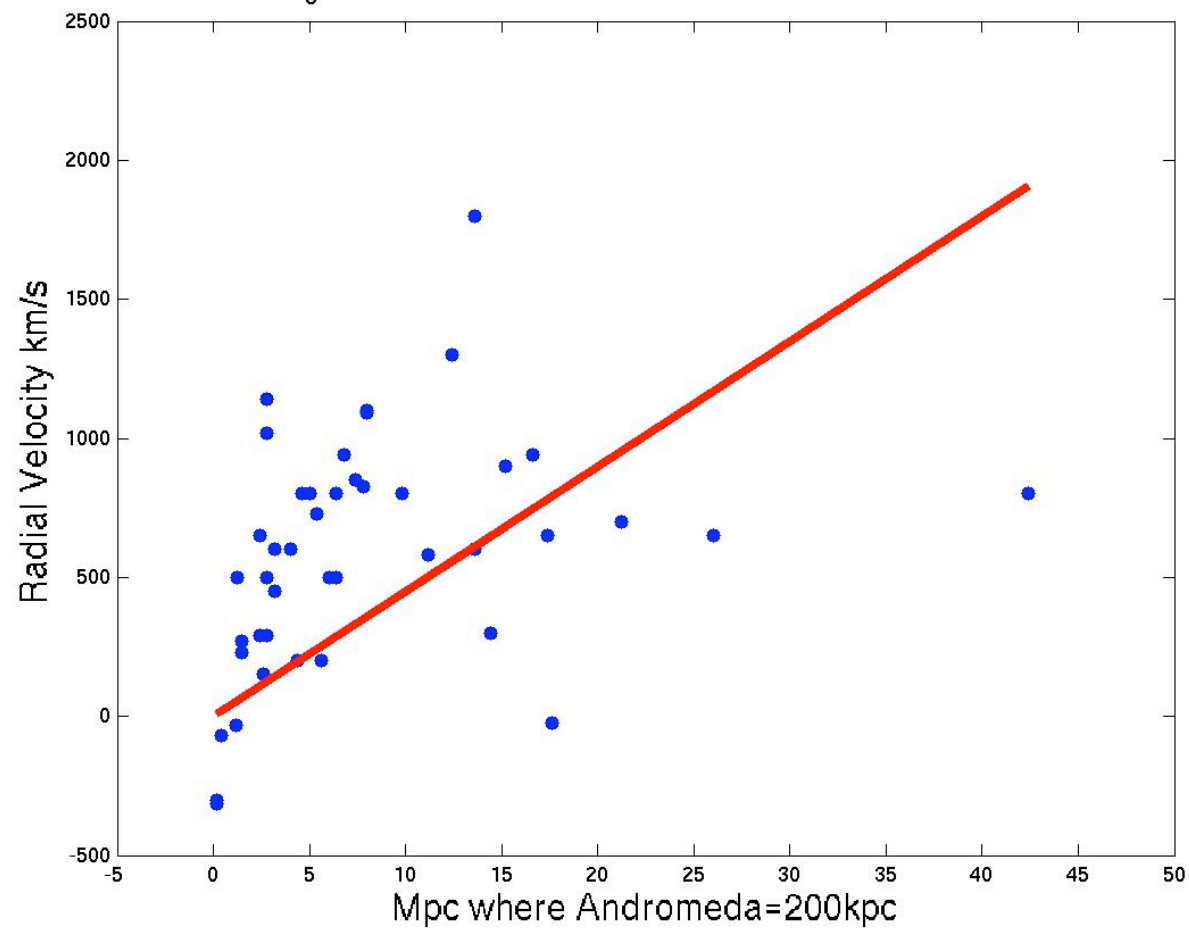


First published radial velocity vs distance **diagram!**



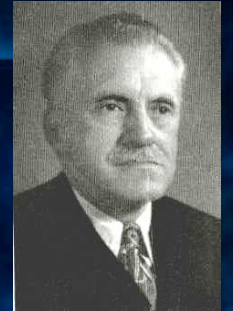
Knut Lundmark (1924)

$H_0 = 44.9373 \pm 13.8$ w/o solar motion correction





Wirtz & Strömberg (1924/25)



- Wirtz (1924 AN 222, 21)
 - Uses data like that of Lundmark (1924) & claims a log-diameter (distance) vs velocity relation: $v(\text{km}) = 2200 - 1200 \times \log(D_m)$
- Strömberg (1925 ApJ 61, 353) [Mt Wilson]
 - Uses magnitudes as a proxy for distance
 - “no sufficient reason to believe there exists any dependence of radial motion upon distance from the sun”
 - Globular Cluster Relationship →

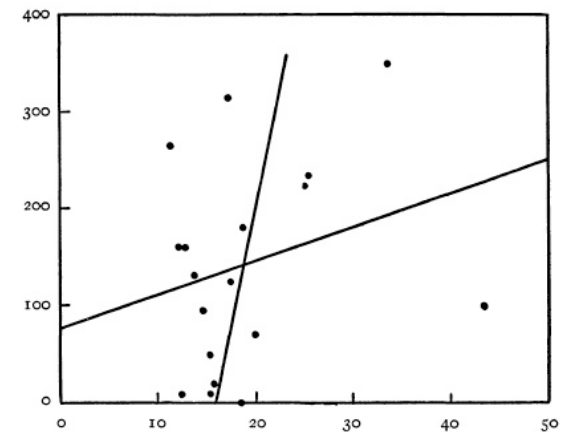
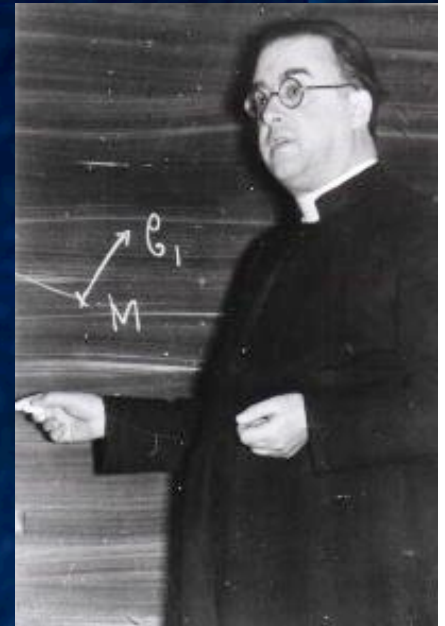


FIG. 2.—Scatter diagram showing correlation between radial velocities without regard to sign (ordinates) and distances in kiloparsecs (abscissae) for globular clusters.

Georges Lemaitre (1925)

- Discusses a non-static de Sitter world
 - Linked it to current observations:
“Our treatment evidences this non-static character of de Sitter’s world which gives *a possible interpretation of the main receding motion of spiral nebulae* (Journal of Math. Phys 4, 188)
- Unlike Silberstein’s previous work (1924) his treatment contained only redshifts: $\Delta\lambda/\lambda=r/cT$
- BUT: No discussion of an expanding universe



Georges Lemaitre (1927)

- Independently derives Friedman's equations with a time-dependent space curvature $R(t)$ but also including a radiation pressure!
 - First introduction of thermodynamics in relativistic evolutionary cosmology
 - Showed that the cosmological equations could be satisfied by an expanding universe
- The velocity of recession is *“the apparent Doppler effect due to the variation of the radius of the universe”*
- Very different understanding from Friedman?

Georges Lemaitre (1927) cont'

- Derives a distance versus radial-velocity relationship (The Hubble Constant) for spiral nebulae via the data of:
 - G. Strömberg (1925 Mt. Wilson - radial velocities)
 - Hubble (apparent magnitudes, 1926 ApJ 64,321)
- Using 42 galaxies he found values of 625 & 525 km/s/Mpc
 - Mentions previous attempts by Lundmark (1924) and Stromberg (1925)

Georges Lemaitre (1927) cont'

Unfortunately...

- Published in the Annales Scientifique Bruxelles
- Einstein called his physically expanding universe solution “abominable”
 - The 2nd time Einstein rejects this solution, why!?
- Paper is forgotten by everyone (including Eddington who saw it) just like Friedman's!!
- Later was published (in truncated form) in MNRAS in 1931 (thanks to Eddington)

Howard Percy Robertson (1928)



- Derives a reformulated De-Sitter soln
- “We should expect a correlation between velocity, distance and radius of the observable world:
 - Mentions Weyl’s 1923 paper
 - Similar to Lemaitre’s 1925 paper
- Derives Hubble’s constant via distances of Hubble and radial velocities of Slipher
 - $H_0 = c/R = 462 \text{ km/s/Mpc}$
 - 1928 Phil. Mag. 5, 31, 835

$$v \cong c \frac{l}{R} \dots$$



Edwin Hubble (1929)

- Uses distances to 24 nebulae & their redshifts to derive a linear velocity-distance relation
 - Mentions Lundmark's work (not Lemaitre's)!
- 1931: Accuracy increased with 40 more
 - Debate on linear relationship ended here
- **HOWEVER:** Hubble drew back from explicitly advocating the expanding universe! He preferred the De Sitter?

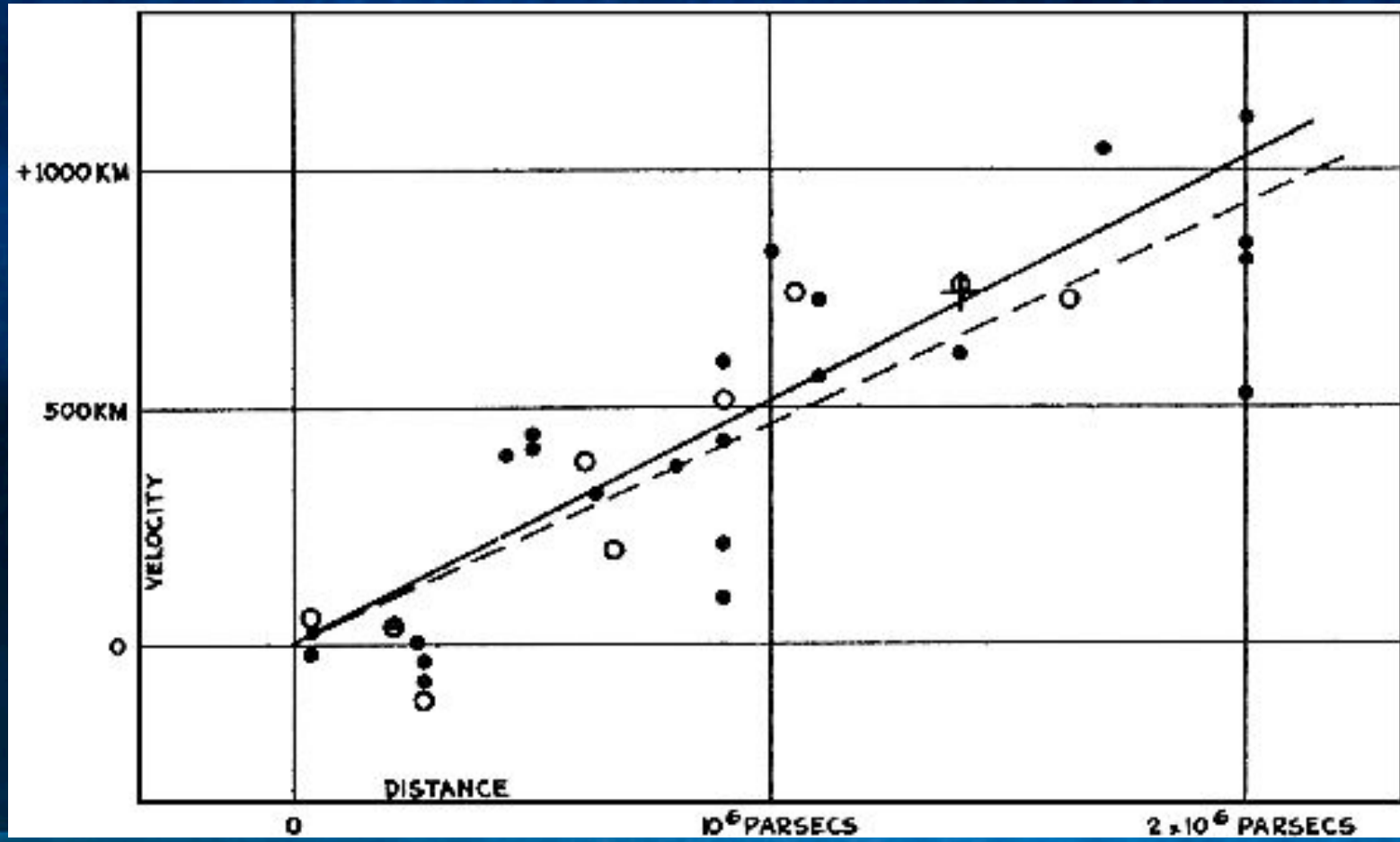


Edwin Hubble (1929)

- “A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE”
 - Proc. Natl. Acad. Sci. USA 15, 168–173
 - $v = H_0 \times D$
- 24 Objects: $H_0 = 465 \pm 50$ km/s/Mpc
- 9 “Groups”: $H_0 = 513 \pm 60$ km/s/Mpc
- $t = 1/H_0 \sim 2 \times 10^9$ yr old (very young?!)



Edwin Hubble (1929)



Lemaitre & Oort (1931)

- Lemaitre: speculates Universe began as a primeval atom (May 9, 1931 Nature)
- Lemaitre's 1927 paper is finally published (MNRAS 91, 483). But does not contain his values of H_0 !!
- Oort recalculates & adjusts nebulae absolute magnitude assumptions and finds $H_0=290$ km/s/Mpc

Richard Tolman (1934)

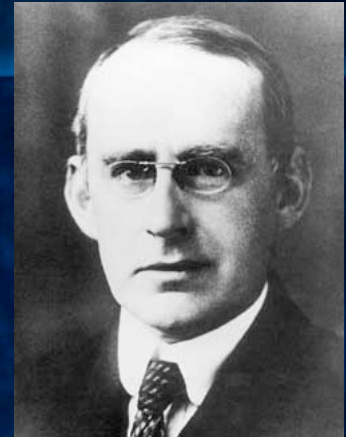
- Informed of Lemaitre's work by de Sitter & Eddington (1931?)
- Leads to publication of "Relativity, Thermodynamics, & Cosmology" (Reissued in 1987)
- Shows that Planck's black-body radiation in an expanding universe cools but remains thermal



RELATIVITY
THERMODYNAMICS
AND COSMOLOGY
RICHARD C. TOLMAN



Arthur Stanley Eddington



- Eddington really promoted the idea of the expanding universe starting ~1930
 - Realized the Intimate relationship between Lemaitre's 1927 paper and Hubble & Humason observations
- It was Eddington not Hubble that made it acceptable.

Expanding Universe to the CMB

- We now have theoretical & *some* observational evidence of an expanding Universe
- However, where is Tolman's black body radiation from the Big Bang?

Unknown signals and temperatures

- In 1940 and 1941 several observations are made of the CMB, but are not understood as such
- Lets look at these observations by Adams, Dunham, Merrill & McKellar (and a funny comment from Herzberg)
- Then we will jump back to the theory and more observations in subsequent years

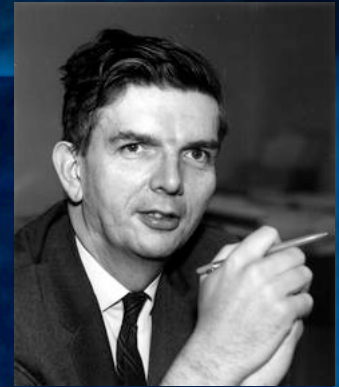
Adams, Dunham, Merrill, McKellar

- 1940: Adams, Dunham & Merrill (Mt. Wilson)
 - observe several unidentified absorption lines including one at 3874.61Å in the ISM
- 1940: McKellar (Dominion) identifies CN line
 - Realizes it is the first molecule discovered in interstellar space!? (along with CH & NaH)
 - ‘the maximum “effective” temperature of interstellar space would be 2.7°, 2.1° or 0.8°K’
 - 1940, PASP 52, 187

Adams, Dunham, Merrill, McKellar

- 1941: CN line observations of McKellar are confirmed by Adams using ζ Ophiuchi
- 1941: McKellar confirms calculations
 - ‘the “Rotational” Temperature of Interstellar Space is about 2°K’, 1941, PASP 53, 233
- 1950: Hertzberg, Spectra of Diatomic Molecules
 - “From the intensity ratio of the lines with $K=0$ & $K=1$ ***a rotational temperature of 2.3° K follows, which has of course only a very restricted meaning***”

Robert Dicke (1946)

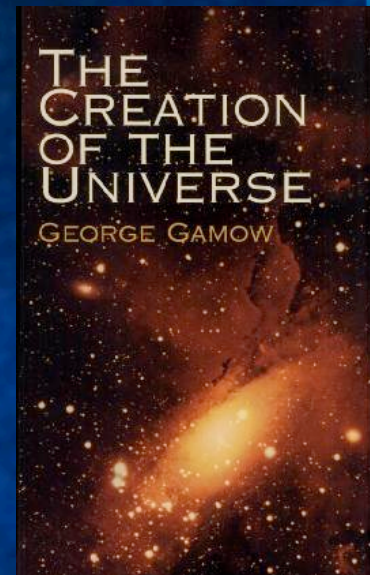
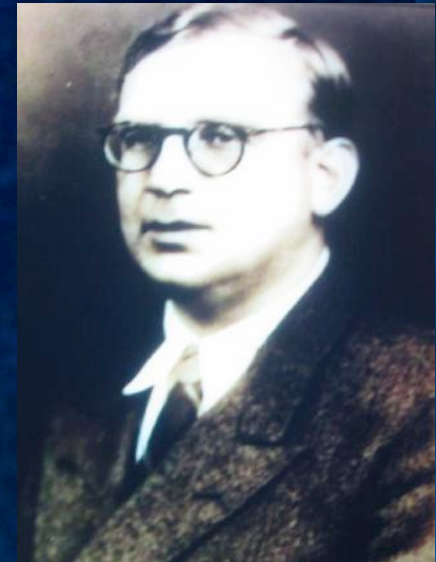


Phys Rev v70, p340 “Atmospheric Absorption
Measurements with a Microwave Radiometer“

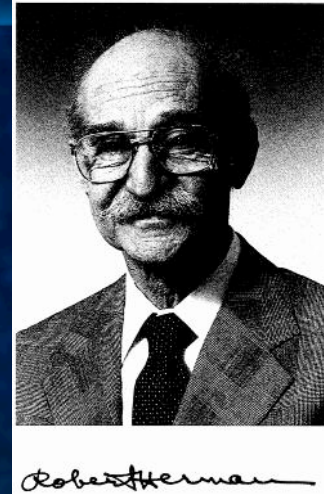
- “It is also found that there is very little ($< 20^{\circ}\text{K}$) radiation from **cosmic matter** at the radiometer wavelengths”
- “However, the absolute accuracy of this result was not high ($\pm 20\text{K}$) for a number of experimental reasons. In any case, a small amount of cosmic noise if distributed uniformly in direction does not introduce much error...”

George Gamow (1946)

- Develops a big bang model of the Universe (3×10^9 years old)
 - Phys Rev 70, 572
 - Explains the abundance of metals in The Universe via “Big Bang Nucleosynthesis”
 - Supports Lemaitre & Tolman’s theory of the expanding universe
 - 1952: $T=50\text{K}$ in “The Creation of The Universe”, page 40 →→→



Gamow Alpher & Bethe? Herman



- 1948: $\alpha\beta\gamma$ paper: Alpher Bethe Gamow
- Predict that a black body spectrum “not higher than 5K” should exist
- Gamow said the 5K spectrum would NOT be detectable (in letter to Ralph Asher Alpher)
- In 1949 Alpher & Herman get $T=28K$
- In fact none of them believe it is detectable

1946-56: Hoyle, Bondi & Gold, B²FH

Hot Big Bang cannot produce heavy elements?

Alternatives to Lemaitre's Big Bang Theory?

- 1946: Hoyle: collection of very hot nuclei would assemble into iron
- 1948: (Hoyle) & (Bondi & Gold) publish their Steady-State Theories of The Universe
- 1954: Hoyle finds stellar fusion can synthesize elements between carbon and iron
- 1956: B²FH Theory of Stellar Element

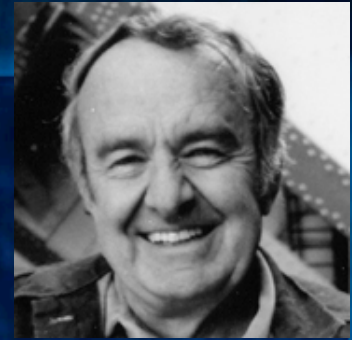
1950: Fred Hoyle & The Big Bang

During a Radio Interview Hoyle ridicules the
“primeval atom” theory by calling it
‘The Big Bang’

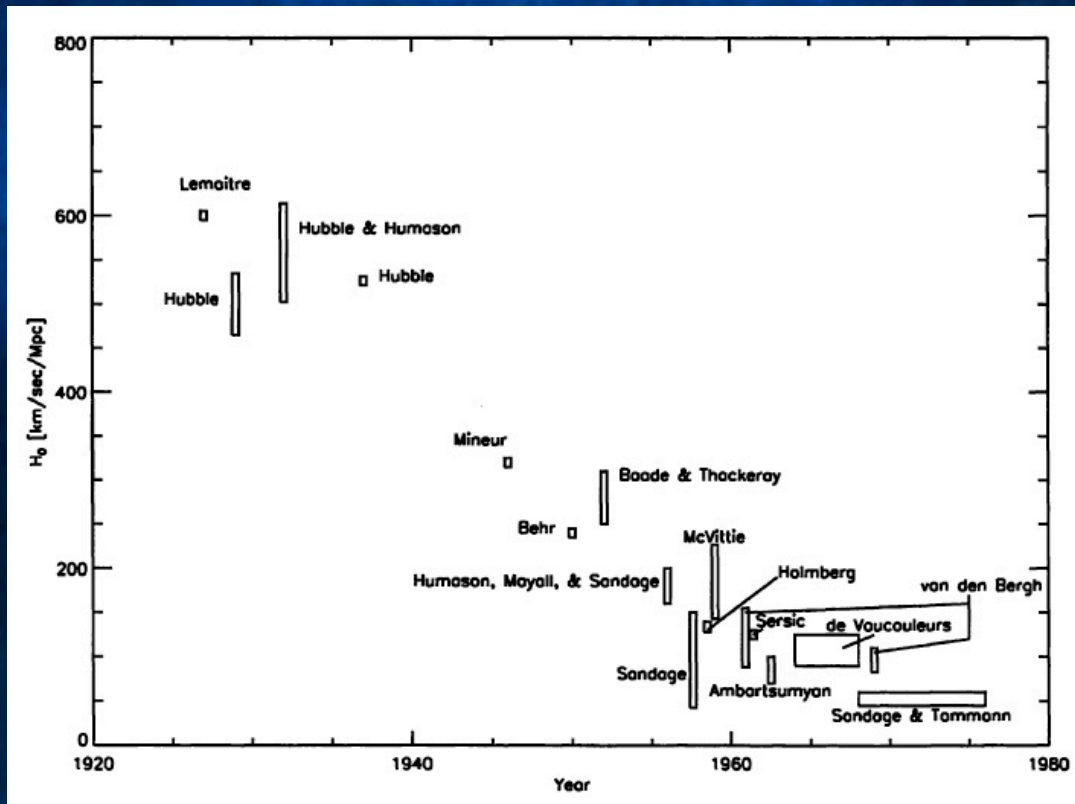
1955 & 57 Le Roux & Shmaonov

- Emile Le Roux's survey at $\lambda = 33$ cm found an isotropic emission $T = 3 \pm 2$ K
 - Suggested it was of extragalactic origin?
- Tigran Shmaonov measured a direction independent radiation at $\lambda = 3.2$ cm
 - "The absolute effective temp. of radiation background ... appears to be 4 ± 3 K"
 - It was not until the 1980s that he realized what he had detected?

1958 Allan Sandage

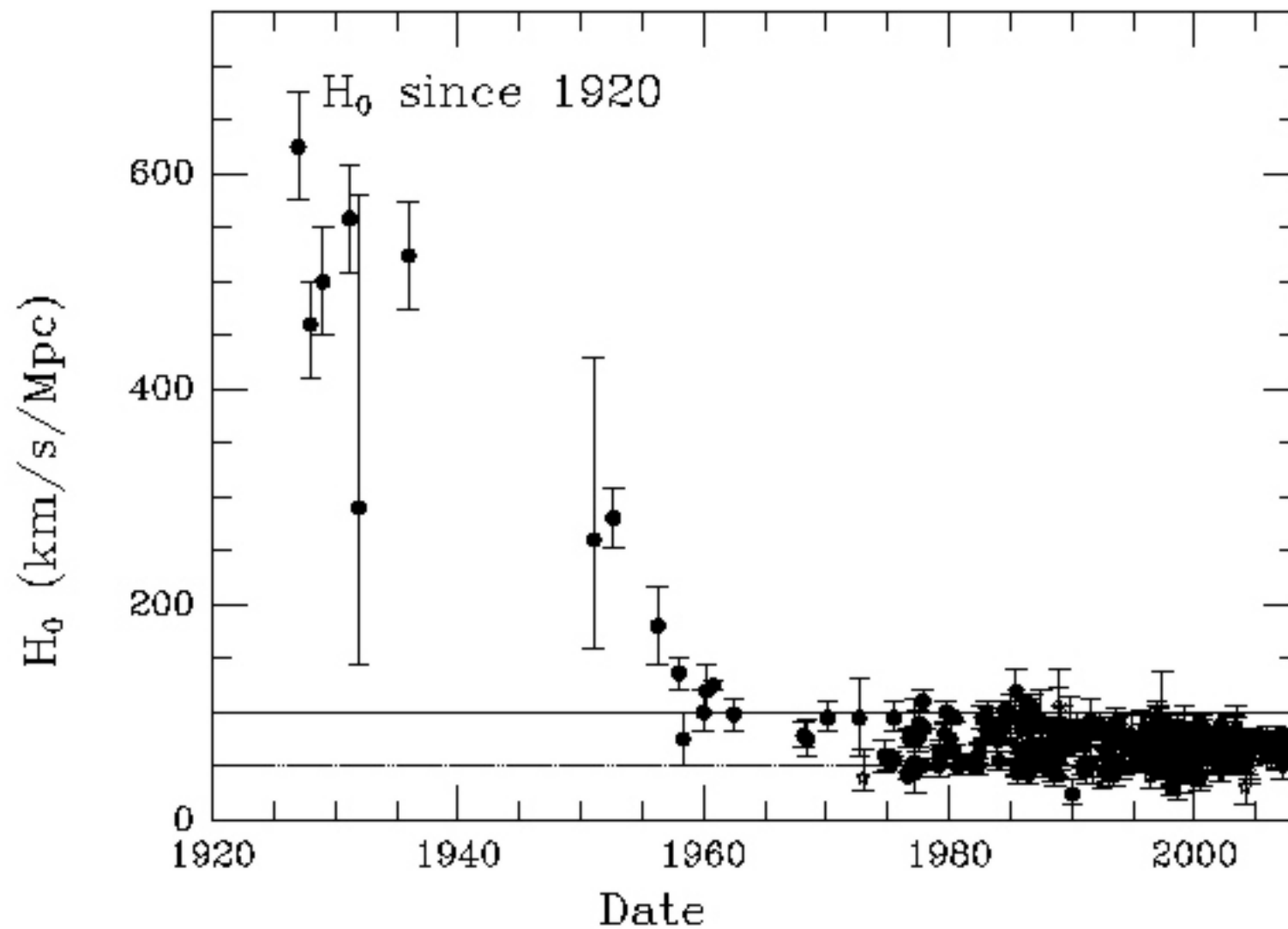


H_0 gives an age of $\sim 13 \times 10^9$ years



V. Trimble '96

Via John Huchra...



Echo I Satellite (1960)

- Bell Laboratories (Holmdel NJ) constructs a very sensitive radio telescope
- Purpose was to study reception of radio signals passively reflected from the Echo I satellite
- Echo I was the first Telecommunications satellite launched by NASA (Project SCORE was the first ever in 1958)

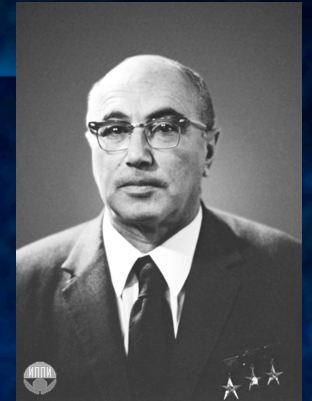
Echo I Satellite



Early 1960s Work: Dicke & Peebles

- Bob Dicke & Jim Peebles re-derive Gamow & Alpher's CMB prediction
 - They recall Dicke's 1946 paper with $T < 20\text{K}$
 - Dicke & Peebles March 1965 SSRv 4, 419 predict $T_{\text{cmb}} = 10\text{K}$ [page 444]
 - Dicke's group decides to look for a Hot Big Bang afterglow (Brans-Dicke Cosmology)
- Dicke, Peebles, Wilkinson, Roll & others start construction of a small radio telescope using a Dicke Radiometer ($\lambda \sim 3\text{cm}$) [mentioned in 1965 paper]

Early 1960s Theoretical Work



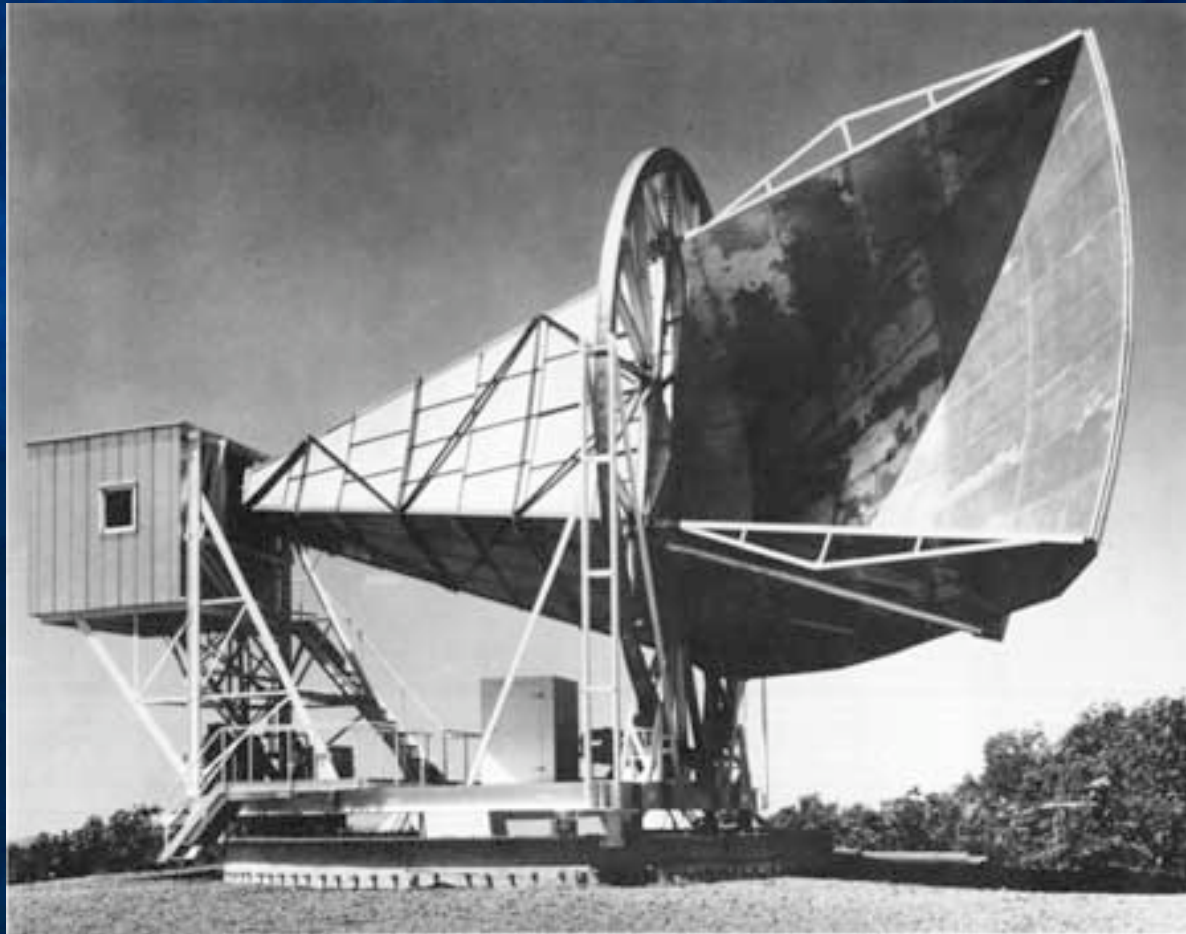
Yakov Zel'dovich

- Recalls Gamow's work
- Calculates $T=20\text{K}$ (1963 SovPhys Usp 6, 475)
- Puts Andrei Doroshkevich & Igor Novikov to work on it
- Was to support his Cold Big Bang Model
 - He didn't think you could synthesize elements in the Hot Big Bang model of Gamow et al.
 - First revival of Big Bang theory since Gamow, Alpher & Herman's work

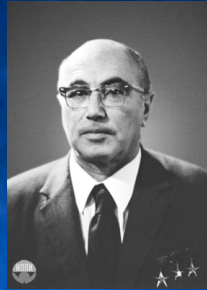
Bell Labs Radio Telescope

- 1963: The Telescope starts to be used for Radio Astronomy
- Was the most sensitive instrument in the world for the detection of radio waves from large areas of the sky
- Used traveling wave maser amplifiers

Bell Labs Radio Telescope



1964: Doroshkevich & Novikov



- Prompted by their group leader Zel'dovich to investigate Gamow's prediction
- They show that the *Relict Radiation* should be **detectable** (contrary to Gamow's comments)
- It should be found in the microwave regime **where other galactic sources have weak emissions**

1964: Doroshkevich & Novikov

- Mention that microwave detections of Ohm (1961)* would suffice for testing this prediction
 - Ohm had found an excess temperature of $T=2.3\pm0.2$ K in his antenna at 11cm (CMB!)
- The D&N paper is unnoticed by Penzias & Wilson AND by the Dicke group
- Princeton is unaware of Ohm's instrument a mere 35 miles away!?

*Ohm 1961 "Project Echo Receiver" B.S.T.J v40, 1065

Bell Labs Telescope - Astronomy

- Original intent was to measure radiation from interstellar emission in our galaxy (7.35cm)
- Accurate measurements required that all sources of noise be taken into account
- Astronomers Penzias & Wilson found a source of noise that was direction independent
- They could not rid themselves of the noise nor explain its origin
- The source had to be instrumental or cosmic

Penzias & Wilson

- Penzias mentions the noise “problem” to his friend Bill Burke
- Burke recalls hearing about a talk by Jim Peebles via Ken Turner who mentioned a 10K radiation from The Big Bang they (Princeton) want to detect

Penzias & Wilson



Penzias, Wilson, Dicke

- Penzias contacts Dicke about his noise problem
- They realize that Penzias & Wilson have detected the Cosmic Microwave Background
- Found temperature to be close to 3K
 - Not Dicke's 10K from 1964

1965: Penzias, Wilson, Dicke

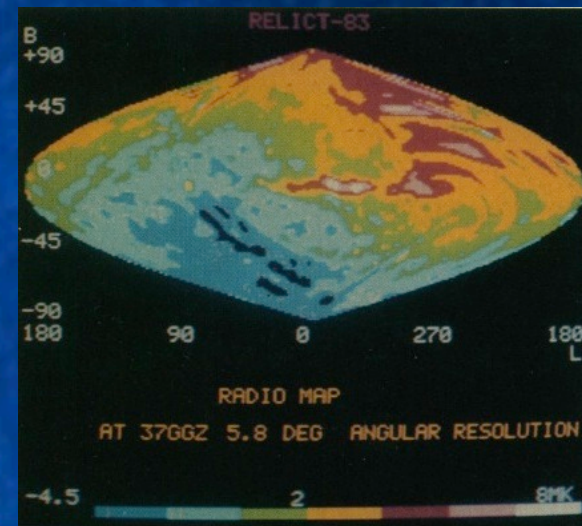
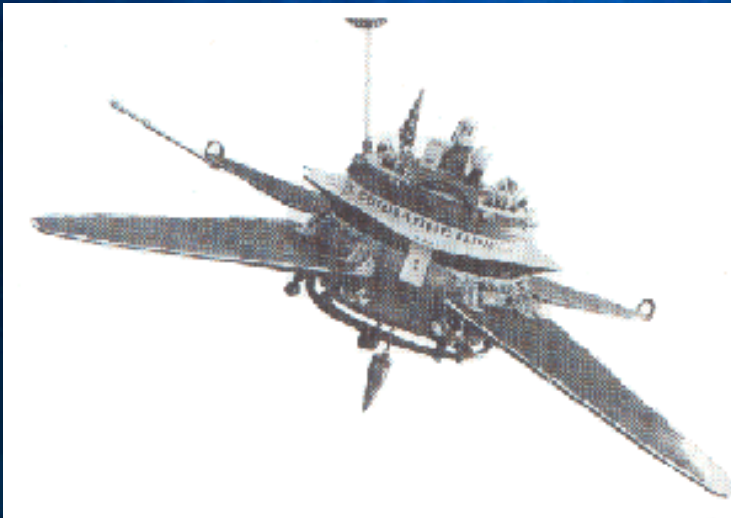
- 1965: Publish two papers in The Astrophysical Journal on the detection of the CMB
 - One is a theory paper by Dicke et al.
 - The other is an experimental paper by Penzias & Wilson

1978: Penzias & Wilson

- They receive the Nobel Prize in Physics
- Penzias & Wilson acknowledge the D&N ground breaking paper in their Nobel Prize speech

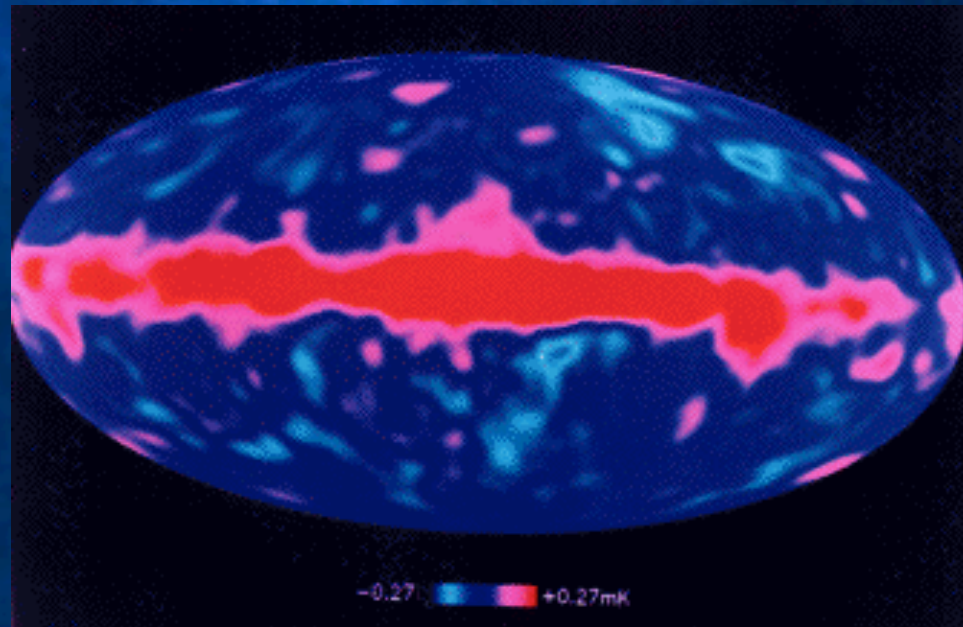
CMB Dipole & Quadrupole

- Henry 1971 Nature, Vol. 231, p. 516-518
 - First to measure dipole $L(\text{true})/L(\text{null}) > 200$
- 1983-4: Prognoz-9/Relikt-1 (USSR)
First to measure CMB Quadrupole?



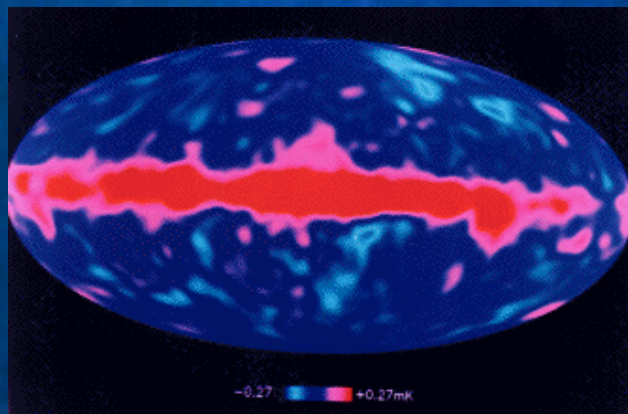
April 1992: COBE

- First evidence for CMB Anisotropy
- Beautiful 2-D map of the early universe is shown to the press



2006: Mathers & Smoot (COBE)

- Recall that in 2006 Mathers & Smoot also received the Nobel Prize for their map of the CMB



A couple of other comments

- Novikov, Doroshkevich, Dicke should also have received the Nobel?
- What about Alpher, Bethe, Gamow?
 - Gott: “Gamow's prediction of the CMB radiation and getting it's temperature right to within a factor of 2 was a remarkable accomplishment -- rather like predicting that a flying saucer 50 ft in width would land on the White House lawn and then watching one 27 ft in width actually show up. One could call it the most remarkable scientific prediction ever to be verified experimentally.”
- Hubble gets credit for expansion of The Universe and should not?

A few references used herein:

Kant: <http://records.viu.ca/~johnstoi/kant/kant2e.htm>

<http://www.astro.ucla.edu/~wright/CMB-dipole-history.html>

Kragh & Smith 2003, Hist. Sci., xli

Partridge 2002, Moriond 2002 “Pre-History of CMB Studies”

<http://moriond.in2p3.fr/J02/Talks2002/B.Partridge/LesArcs.ps>

Gamow: <http://books.google.com/books?id=5awirwgmVaoC>

Gott: <http://books.google.com/books?id=MME33bSTCDsC>

Tolman: <http://books.google.com/books?id=1ZOgD9qIWtsC>

Kragh: Cosmology & Controversy (1996)

Duerbeck & Seitter: In Hubble's Shadow

Duerbeck & Seitter: Carl Wilhelm Wirtz - Pioneer in Cosmic Dimensions

This Talk:

<http://astrophysics.arc.nasa.gov/~mway/EXP.pdf>